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3D Printing Process: A Review of Recent Research

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ABSTRACT

3D Printing (3DP) is an umbrella term that covers manufacturing technologies and processes that offer a wide spectrum of producing components and parts of variety of materials. 3DP is bound to revolutionize design, breaking barriers of geo-political terrains, economic tendencies and social status of nations. With the inception of new technologies and processes, it becomes challenging task for the researchers to investigate the effect of process parameters on performance measures (quality and functionality) and their best combination that yield desired results, in terms of quality characteristics. Researchers have established relationship between process parameters and performance measures and also suggested suitable combination of input parameters that yield desired results. In this paper, an attempt has been made to present an overview of the recent research that identified the importance of process parameters, their effect and optimization.

Keyword: 3D Printing, Process parameters, Performance parameters, Optimization

INTRODUCTION

The manufacturing sector is evolving from traditional methods of manufacturing to computer controlled, Robot assisted sophisticated modern technologies, Capable of producing what the customer demands, since the customer has become king with the awareness and his hunt for excellence and is no more adaptable to inferior quality of product and services. The world has shrunk to a global village with superfast telecommunication technologies empowering the customer with latest product and technologies and also providing him

the exposure to the distant manufacturers breaking all the barriers of geographical locations. With the development of manufacturing and servicing standards at international level, the manufacturers are striving hard to survive at this age of global competition, the introduction of 3D Printing process was also result of such crumbling pressure exerting environment, where the manufacturers were not allowed to produce prototypes/ components in their span of time and thus iconing the rapid prototyping. The hectic condition of

competitive environment in manufacturing sector led to adapt modern technologies that are adaptable with the quick changes in demand like lean manufacturing. The 3DP is now evolved beyond RP and the 3D Printers are being installed on shop floor for mass production and also as domestic printer for Do-It-Yourself (DIY) manufacturing. ^[1]

2. 3D Printing Process

2.1 Introduction

3 Dimensional printing (3DP), As the name implies, is similar to inkjet printing, in which the ink is propelled from the nozzle of the printer in form of jet, The raw material in 3DP is in the form of filament that is slightly heated at the time of ejection and the extruded on the bed, where the component is manufactured, On the exit, the outer core of the filament is in the semi molten form, that is fused with the earlier formed layer and solidifies to form the product.

On the basis of raw material form the process is categorized, the raw material may in the powder form, semi liquid form or filament form.

The 3DP consists of three steps:

- i) Preparation of model: The proposed design of the model is first developed in some CAD software like AutoCAD etc or already produced component is converted into CAD model using Co-Ordinate measuring machine
- ii) Conversion of CAD data into Standard Tessellation Language (stl): The CAD file is then converted into *.stl format, that is capable of converting the design features into manufacturing parameters
- iii) Manufacturing: The received data comprising of manufacturing parameters is executed to produce the desired model. ^[2]

2.1 Types of 3DP:

On the basis of raw material processing the process is categorized in four types:

2.1.1 Stereo Lithography (SLA):

The raw material in this process is in the form of liquid, a photo polymer resin that solidifies in the presence of laser beam. An Ultra violet laser beam is directed and traces along the horizontal plane as directed by *.stl format data. The raw material is placed inside a vat over the movable perforated platform, just below the surface of the polymer. The path or trace of the LASER beam obtained from 3D Software in the form of *.stl file, solidifies the desired profile, another layer is then

hardened by moving the platform in downwards direction, thus completing the object layer by layer.

Figure 1 Stereo Lithography

2.1.2 Fused Deposition Modeling (FDM):

The raw material in this process is in the form of filament of thermoplastic, heated up to fusion temperature then forced to squeeze out of the jet nozzle, extruded filament is then fused binding two consecutive fibers. These fibers add up to form layer and hence whole solid model.

Figure 2 Fused Deposition Modelling

2.1.3 Selective Laser Sintering (SLS):

The raw material in this process is in the form of powder hence can be extended to any material, that can be powdered like metals, Alloys, Ceramics and Nylon etc. The powdered material is mixed with a binder material and the laser is moved to produce the desired contour hence providing stiffness to the material forming the hardened layer, The platform is lowered subsequently another layer of powdered material is compacted by a roller after

which it is ready for the laser. Layers are formed to produce components. [3]

Figure 3 Selective Laser Sintering

2.1.4 Selective Deposition Lamination (SDL):

This process is simple and lengthy in which the layers are given shape individually and layers are stick together by applying adhesives and pressure. The strength is high as well as the consumption of adhesives.

Figure 4 Selective Deposition Lamination

3. Literature Review

The increasing importance of 3DP attracted the focus of researchers and lead to investigation of:

- i) the importance of process parameters
- ii) what effect do they yield (individual and in-combination) on mechanical properties
- iii) A perfect combination of input parameters, that yields the desired result.

The experimentation requires a design or model (design of experiments) to conduct the experi-

mental run, the obtained data (result) thus, is analyzed by applying certain technique (ANOVA) to find the effect of variation of process parameters on the mechanical properties.

Finally, optimization technique is applied to find the best combination of process parameters for desired mechanical properties.

The prime importance is parametric optimization, since no investigation is complete without a suitable solution; hence main stream researchers have applied various optimization techniques in order to find suitable solution.

The researchers have considered the following parameters as the most significant:

- i) Layer thickness
- ii) Print orientation
- iii) Bead temperature
- iv) Air gap
- v) Raster angle
- vi) Build orientation
- vii) Road Width
- viii) No of contours [4],[5],[6].

The mechanical properties that are under consideration are:

- i) Ultimate tensile strength
- ii) Bending strength
- iii) Compressive strength
- iv) Crushing strength
- v) Flexural strength
- vi) Shear strength
- vii) Hardness
- viii) Surface finish
- ix) Impact [7][8][9]

The latest paper available in this field is by Jason T. Cantrell et al., considered to compare the effect of orientation on the mechanical properties (shear and tensile) of ABS and Poly Carbonate (PC) materials processed by two FDM type of printers: Ultimaker® 2 and Fortus 360mc™ and the orientation considered +450 /-450 and 00 / 900 respectively.

The result of tensile and shear test are also taken respectively, as follows:

Poisson's ratio 0.36/0.38 and 0.37/0.36

Young's modulus(MPa) 1960/ 2020 and 2020/1910

Offset yield strength (MPa) 30.3/30.0 and 32.0 and 29.0

Tensile strength at yield (MPa)32.8/31.9 and 33.5/30.7

Elongation at Break (%) 8.89/7.14 and 2.34/ 2.79

Tensile stress at break (MPa) 29.6/30.1 and 30.7/29.4

Strain energy density (MJ/m3) 3.17/1.46 and 2.14/1.66

They applied graph technique to compare and evaluate results and concluded that For Young's modulus and Poisson's ratio, ABS specimens exhibited isotropic nature but exhibited anisotropic

nature for tensile strength at yield point and PC specimens revealed anisotropic properties (under tension).^[10]

Clayton Neff et al. in their research presented the effect of vapour polishing on the mechanical properties and surface finish of ABS.

Their argument is that mechanical properties such as strength and elongation to failure are reduced in the parts printed by 3DP, relative to traditional manufacturing processes and is a function of build orientation and other process parameters. Properties like reduced strength, stiffness and ductility are produced due to discrete stacking of cross-sectional layers, Vapour deposition eliminates the surface defects and micro-porosity hence improve surface finish, parts were coated by vapour deposition after being printed by FDM process of ABS material. Experimentation consisted of printing ten specimens of 1, 2 and 4mm thickness and their before and after treatment properties were tested and percent increase was recorded as follows:

Average roughness changes (Ra) (For 1 micron thickness)

Ra ± Standard Deviation 37.18±14.55 10.13 ± 8.23

Ra ± Standard Deviation 44.41±15.06 12.39 ± 8.86

Graph technique was applied to compare before and after treatment and they concluded that approximately 51% effect was noted.^[11]

Ahmed et al. in their research focused the six basic process parameters to link with creep and recovery behavior of ABS printed by FDM. They applied definitive screening design (DSD) model to design their experiment and Artificial Neural network (ANN) to give optimal solution.

The six parameters with three levels are:

i) Layer thickness	0.127	0.254	0.3302
(A)(mm)			
ii) Air gap (mm)	0	0.25	0.5
iii) Raster angle	0	45	90
(Degrees)			
iv) Build orientation	0	45	90
(Degrees)			
v) Road Width (mm)	0.4572	0.5177	0.578
vi) No. of contours-	1		10

The experimental run was conducted by applying DSD and 16 trails to find the range of Creep compliance(CC) ($\mu\text{m}^2/\text{N}$) 1,330.624 to 21154.423 and recoverable compliance (RC) ($\mu\text{m}^2/\text{N}$) 1,096.198-1,698.241. The optimum solution is given:

Optimum parameter settings

A	B	C	D	E	F	
CC	0.127	0	0	17.188	0.4572	10

The deviation found between expected and actual value is: 2.74%.^[12]

Lederle et al.^[13] analyzed the mechanical properties of parts produced by FDM in the Oxygen environment and in the absence of oxygen (Nitrogen), on two materials (i) Acrylonitrile butadiene Styrene (ABS) and (ii) Polyamide, the mechanical properties, they focused, were (i) tensile strength, (ii) elastic modulus, (iii) elongation at peak stress & (iv) elongation at breakage, of parts produced on a UP Plus 2 type of 3D-printer from Tier Time Technology company to print the components. They found the followings results:

	Ultimate Tensile Stress (N/mm ²)	Elastic Modulus (N/mm ²)	Elongation at peak stress (%)	Elongation at breakage (%)
Air	19.4	E=1.56	3.9	4.4
Nitrogen	49.6	E= 0.07	3.9	10.7

They applied graph technique to compare the results and concluded the nitrogen gas atmosphere was more suitable for yielding best results. The possible reason is oxygen atmosphere produces complex oxides that don't exhibit regular pattern of the polymers, bypassing the basic properties of the materials and also suggested optimized values as:

Temp: 200-2800C Environment: Nitrogen.^[13]

Farzadi et al.^[29] focused on the consequences of layer printing delay on mechanical properties and dimensional accuracy of parts printed on a 3D-printer (Z450, Z Corporation, USA), of FDM type of printing technology. The material used was ZP150 powder. The method they applied is Analysis of Variance (ANOVA) technique of statistical model to process the data obtained. The only parameter varied was delay in printing layer. Other parameters were kept constant. The delay taken, varied in four different time sets, measured in mili- seconds:

And the relevant properties were:	50	100	300	500
Elastic Modulus (MPa)	0.6	-	-	1.8
Compressive Strength (MPa)	0.0	0.4	0.7	0.9
Compressive Stress (MPa)	0.0	0.4	0.5	0.7

From the abovementioned data they concluded that layer printing delay has significant effect on compressive strength but yields minor effect on their structural properties. They also gave optimum value of layer printing delay and the reason is when the layers are superimposed each other the crust of the filament is in the fused form keeping the core in solid form hence providing adequate strength at the micro level because of the capillary action, The

delay in the printing decreases the temperature of the filament, thus providing solidification to the crust of the filament, resulting in reducing capillary action resulting in decreased compressive strength and slight effect on structural properties. ^[14]

Carneiro et al. ^[15] focused on the raw material, Polypropylene (PP), during the entire manufacturing process in FDM. The PP was taken in the form of powder to manufacture the filament, which is later used to print a component. The entire process applied two levels (i) Technique level and (ii) material level. The material chosen PP was taken of two types (a) Glass fiber re-enforced (GRPP) and (b) Neat PP.

The infill was:	20	60 and 100 %
Layer height:	0.1	0.1 0.1mm
Raster angle:	45	0 90 degrees

The corresponding values of Ultimate tensile stress (MPa) and elastic modulus (MPa) were; 14 22 27 and 0.9 1.1 and 1.3

The partial results were, (a) Printing Orientation was significant on the adhesion adjacent layers, (b) Layer thickness has little influence on the mechanical properties (c) The Infill percentage has strong effect on mechanical properties (d) The use of reinforcement is also effective (e) The loss of mechanical performance is affected by 20-30% by changing the input parameters.

Conclusion of the above study indicate that (a) printing orientation is of utmost importance and will always result in significant effect on strength, The fiber building and its growth in the lateral direction provides high strength, that we know from the ages, The same reason for the strength of forged Iron as compared to Cast Iron (b) The capillary action in the fused PP is so high that two successive layers amalgamate with each other densely and produce a strong bonding at the crust level that is why increasing or decreasing layer thickness will result in little effect on strength (c) The packing factor has a direct impact on strength and weight, Thus infill ratio will always result in varied mechanical properties (d) Again reinforcement will provide fiber to the structure, hence adding strength and (e) Performance level of any product is measured in physical terms like strength, toughness, resilience and hardness etc., Varied mechanical properties will affect the performance significantly. ^[15]

Casavola et al., ^[16] applied classical laminate theory to describe orthotropic mechanical properties of the components produced by FDM. They compared two main materials PLA and ABS to produce components, whose properties were testified. The properties were Young's Modulus (E), Ultimate Tensile Strength (UTS), and was concluded that PLA was stronger than ABS, whereas the ABS was more brittle, PLA has a lower capacity to withstand temperature. The strength of any material depends on various factors

like size of fiber, orientation of fiber, grain size and its distribution, capillary action and affinity between grains and boundaries, PLA scores on all the accounts with respect to ABS. ^[16]

Jiang et al. ^[17] applied multi-objective optimization technique using Signal to noise ratio (SNR) and grey correlation degree methods of various input parameters. The process parameters were platform velocity (A), material extrusion speed (B), fiber spacing (C), electro spinning concentration (D), accepting distance (E) and voltage (F) to find the best combination among these parameters. The best combination was found A=16m/s, B=16m/s, C=1.4mm, D=8.7%, E=100mm, F=19kv, The data set was obtained applying grey correlation theory with the objective, smaller the better objective applied to filament diameter and layer height, Whereas SNR determines the order of parameters in which they affect the properties from higher to lowest. The structure is studied with the help of Scanning Electron Microscope (SEM), which exhibited the effect of optimized parameters resulting in well defined stretching of pseudo pods and friendly environment for stem cell growth.

Parametric optimization is the process of selecting a set of parameters that yield the desired result. The cross section of filament diameter is divided into two parts, i) Crust and core, Crust is the outer shell that comes in fusion form once heated till the time of extrusion, while core provides the inner strength to the structure, same is with the layer height and a combination of their appropriate values will result in high degree of accuracy and favorable environment for stem cell growth. ^[17] Torredo et al. aimed in their paper to highlight the disadvantages of 3DP, Anisotropic properties are one of them, and common methods of testing are Analysis of Ultimate tensile stress and impact testing. The processes under consideration is Fused Deposition Modeling and material is Acrylonitrile butadiene Styrene (ABS) blended with six different proportions of Polymers (JUTE, MAYACROM, TiO₂, ZnO, SrTiO₃ and Al₂O₃), the angle taken were zero degrees and 90 degrees, the properties tested were UTS and percentage elongation at break, Printer was MakerBot Replicator (MakerBot Industries, Brooklyn, NY, USA). The printing took place using rectangular fill at zero degrees print orientation and raster angle would change every layer to 90 degrees. The strength of the material depends on the length of the fiber, with which the product is made of; longer the fiber higher is the strength. ^[18]

Lifton et al. ^[19] explored the options of 3DP being included in micro electromechanical systems (MEMS). The objective of their study was to explore the recent manufacturing techniques of 3DP and their comparison with resolution required in MEMS. The study was done on all the five types

of 3DP, SLA, SLS, Micro Laser sintering FDM and polyjet methods.

The process parameters that were considered, Layer thickness, Min feature size (resolution), Material selection, and Maximum size of the model. The properties under consideration were tensile strength, tensile modulus, and tensile elongation at failure, flexural strength and flexural modulus. The outcome of their study was MEMS bandwidth and reasons are shorter turnaround times in design and fabrication, high resolution capabilities. The drawback is that 3DP is not being used at commercial levels.^[19]

3DP is modern technology of ancient concepts and has revolutionize the manufacturing technology, In other words it can be said that the traditional methods like extrusion are automated only and there is nothing new in this technology, Yet the people will take time to understand and adopt the concept, In the mean time the research pattern will set the resolution of 3DP at par with the MEMS.

Tymrak et al.^[20] evaluated mechanical properties, tensile strength, strain and elastic modulus by changing Infill ratio, layer height and print orientation of materials (i) PLA and (ii)ABS using a Reprap 3D Printer(FDM type).Their conclusion was PLA by and large is a superior material than ABS.^[20]

This is the same conclusion which Caterina Casavola had earlier drawn and It has already being explained in the summary of the Caterina Casavola that the strength of any material depends on various factors like size of fiber, orientation of fiber, grain size and its distribution, capillary action and affinity between grains and boundaries, PLA scores on all the accounts with respect to ABS.

Melenka et al.^[21] chose dimensional accuracy and material properties to work on. Their concern was three major parameters that affect the properties most, (i) layer thickness (ii) print orientation & (iii) infill percentage, and properties were (i) longitudinal elastic modulus and (ii) ultimate strength. They applied ANNOVA technique as analysis tool to find that all the three major parameters affect the properties individually but their interaction yield little or insignificant effect on the mechanical properties.

MakerBot Replicator 2 type of printer was used to manufacture the specimen, their sample size was 32, since full fledged 23 factor analysis was performed. The confidence level was 95%, material used was PLA their conclusion was Infill percentage yielded significant effect on longitudinal elastic modulus, then layer height was second greatest effect.^[21]

The atomic packing factor, as earlier explained, provides strength and weight to the material; It also has a significant effect on pattern of solidification,

hence the conclusion in the previous paper match at par with this theory.

Spath and Seitz^[22] explored the effect of grain properties on the micro-porosity of the structure. Flow properties of the grain play important role on various physical properties of the material including micro-porosity, Flow properties like flow ability depends on grain size, grain size distribution, grain shape, humidity temperature and chemical composition. The effect on flow ability and workability was testified. Micro porosity is most affluent property, which determines basic structure. The size of granules was categorized into eight ranges. The granular properties were determined by applying various techniques like Bulk Density (BD), Tapped Density (TD), Hausner Ratio (HR), Carr's Index (CI), Funnel Diameter (FD) and Angle Of Repose (AoR), They concluded that flow ability decreases with the decreasing size of the granule, Additionally, Shrinking sphericity would cause worse flow behavior. The conclusion falls in line with that, the flow rate of the particles is dependent on the mass, shape and size and reduction in these parameters would cause reduced speed hence reduced flowability. Their further conclusion that shrinking sphericity causes worse flow behavior is also explainable since the radius of curvature provides smooth rolling of the grains and the reduction in the curvature would cause collision in- between them, loss of speed and also produce frictional heat taking the flowability at its worst stage.^[22]

Vaezi M, Chua^[23] analyzed the effect of input parameters like binder properties, layer thickness, powder particle size and binder saturation level on the strength and surface finish of components manufactured by 3DP process. The material chosen was ZP102 powder and Zb56 binder of ZCorp. Two combinations of layer thickness were evaluated at two different binder saturation levels. They applied graph method to compare set of combinations of parameters with the tested values at different level. The outcome of their study was that increasing binder saturation level only (and not the layer thickness) would increase in tensile strength and flexural strength, A 35% level increment in the binder saturation level would result in 34.7% and 41% increment in tensile and flexural strength. The decreased layer thickness, from 0.1mm to 0.087 mm, would result in increased tensile strength and reduced flexural strength and worse surface quality and uniformity.^[23]

The result of their experiment is very interesting as the role of the binder is to provide adherence within the particles of the materials and hence increase in binder saturation level would directly increase the strength, be it tensile or flexural, this was expected, the later part is, when the layer thickness is decreased, the tensile strength

is decreased but the flexural strength increases, Layer thickness, as explained earlier would affect tensile strength directly proportional, but inverse proportional of flexural strength is strange and cannot be explained as of now.

Lee et al, ^[24] in their paper focused on the compressive strength based on the direction of printing or anisotropic properties in 3DP. The print orientation was taken as axial (zero degrees) and transverse (Ninety degrees) and the result, compressive strength was 41.26MPa 11.6% higher than that of transverse printing. The reason of higher strength can be explained as length of fiber, longer the better. ^[24]

Weng et al, ^[25] focused on the negative side of 3DP processes, Despite so many good features 3DP is yet to be introduced at industrial level, The major drawback is mechanical strength, that of printed parts is worse as compared to other common manufacturing processes like injection moulding, due to weak points among the layers. The strength of nanocomposites, Acrylonitrile butadiene styrene (ABS) can be improved by adding reinforcement materials like organic modified montmorillonite (OMMT). The process under consideration is FDM and injection moulding whereas the mechanical properties are tensile and flexural strength. The thermal properties are also improved. The research yields the desired result, data shows that tensile and flexural strength are increased considerably and also thermal properties are improved. The strength of the printed parts depends on the affinity of the layers with its neighboring layer leaving some spaces and points as blank. ^[25]

Kellens et al, ^[26] In their next paper they evaluated SLS method of 3DP and pointed that two parameters i) Build height and ii) Volume, are responsible for most of the energy consumption. ^[26]

Sreenivasan and Bourell ^[27] evaluated the same process, SLS and accurately determined percentage of total heat utilized in different components of SLS, i) Chamber heat -- 316% b) stepper motor -- 26% c) roller drives -- 16% and d) laser transmitter --16%.

Later on the basis of heat components, they suggested to develop an improved heat management system that includes energy efficient laser transmitter. ^[28]

Farzadi et al. examined the effect of layer height and print orientation on mechanical properties and physical accuracy. ^[29]

Lee et al. ^[24] measured the compressive strength of parts produced by rapid prototyping by changing the direction of the print, from zero degree to 90 resulting in increased compressive strength from 41.26 to 46.04 MPa, that lead them to conclude that print orientation has a significant effect on the compressive strength, that increased by 11.6% only due to orientation of the printing head. ^[29]

Weng et al, ^[25] in their research compared the tensile strength and elastic modulus of the parts produced by injection moulding and parts printed by 3DP. They also altered the material used in 3DP, ABS by introducing re-enforcement material, Montmorillonite (OMMT). The two processes yielded the following data;

Tensile strength (MPa)	Elastic modulus
Injection moulding	49.94-64.36 1.9-3.2
Printed parts	27.59-39.48 1.2-3.6

They reached to the conclusion that injection moulding process produces good tensile strength and elastic modulus and also re-enforcement material has significant effect on the strength of the ABS. ^[29]

Table 1 Summary of recent research papers

S.No.	Author/ Year	Process Parameters					Mechanical Properties						Remarks
		(A)	(B)	(C)	(D)	(E)	(U)	(V)	(W)	(X)	(Y)	(Z)	
1	Cantrell et al. ^[10]	Orientation [Ultimaker @2]	Orientation [Foruts 360mc™]				Poisson's ratio	Young's modulus	Offset yield strength	Tensile strength at yield	Elongation at Break	Tensile stress at break	Process/ Material FDM/ABS & PC
		(Degrees)	(Degrees)				-	(MPa)	(MPa)	(MPa)	%	(MPa)	
		+45	0				0.36/ 0.38	1960/ 2020	30.3/ 30.0	32.8/ 31.9	8.8/7.14	29.6/30 .1	Conclusion: isotropic nature exhibited (for For Young's modulus and Poisson's ratio) Anisotropic nature found for tensile
		-45	90				0.37/ 0.36	2020/ 1910	32.0/ 29.0	33.5/ 30.7	2.34/ 2.79	30.7/29 .4	

													strength at yield point of ABS. anisotropic properties
2	Neff et al. ^[11]	Acetone vapour deposition (t=1mm)	Acetone vapour deposition (t=2mm)	Acetone vapour deposition (t=4)			Average Roughness Pre processing (Ra)	Average Roughness Post processing (Ra)					Process/ Material: FDM/ABS
		(mm)	(mm)	(mm)			microns	microns					Conclusion: The surface roughness is decreased by almost 30%
		(mm)	(mm)	(mm)			37.18±14.55	10.13±8.23					
		0.82	0.22	0.04			44.41±15.06	12.39±8.86					
		0.20	0.6	0.02			-	-					
3	Mohamed et al. ^[12]	Layer thickness (A)	Air gap	Raster angle	Build orientation	Road Width	No of contours	Creep Compliance	Recoverable compliance				Process/ Material: FDM/ABS
		mm	mm	degrees	degrees	mm	No;	µm²/N	µm²/N				Conclusion:
		-1	-1	-1	+1	+1	+1	1330.624	1096.198				Optimum parameter values are:
		+1	0	-1	+1	+1	-1	3979.747	3009.447				A=0.127
		-1	+1	0	+1	+1	-1	4950.968	4111.691				B=0
		-1	+1	+1	-1	-1	0	2264.466	1945.186				C=0
		-1	-1	+1	0	0	-1	1489.022	1217.957				D=17.188
		+1	+1	-1	0	0	+1	2238.778	1645.631				E=0.4572
		+1	-1	-1	-1	-1	-1	1561.136	1179.775				F=10
		0	+11	+1	-1	-1	-1	6917.07	5058.5965				The deviation is 2.74%
		+1	-1	+1	-1	-1	+1	1411272	1182.01				
		-1	0	+1	+1	-	0	1728.434	1232.326				
		+1	+1	+1	+1	+1	+1	1689.031	1377.069				
		0	0	0	0	+1	0	2224.664	1738.047				
		0	-1	0	-1	0	+1	1755.145	1263.024				
		+1	0	0	0	-1	0	2044.292	1671.334				
		0	0	0	0	0	0	2194.312	1685.341				
		0	0	0	0	0	0	2154.423	1698.241				
4	Lederle et al. ^[13]	Oxygen Environment	Nitrogen Environment				Ultimate Tensile stress	Elastic Modulus	Elongation at σm	Elongation at εb			Process/ Material
							N/mm²	KN/m²	%	%			FDM/ABS & Nylon Conclusion:N

													nitrogen environment is more suitable to improve mechanical properties.
							19.4	E=1.56	$\sigma_m=3.9$	$\epsilon_b=4.4$			Optimum level:Temp-200-280 °C
							-	+	-	-			Environment: Nitrogen
							49.9	0.07	3.9	10.7			
5	Farzadi et al., [29]	Layer Printing	Layer Thick	Ori enta tion				Elastic Modul us	Compr essive toughn ess	Compr essive Strengt h	Compres sive Stress		Process/ Material: FDM/ABS
		mili seconds	mm	Deg rees				MPa	N/mm ²	MPa			Conclusion: Layer Printing Delay has significant
		50	0.10	90				E=0.6		0	0		Effect on :
		100	Do	Do				-		-	-		Compressive Strength
		300	Do	Do				1.8		0.9	0.7		Compressive Stress
		500	Do	Do									Optimum Value=300ms
6	Carnerio et al [15]	Percentag e Infill	Layer Height	Ori enta tion			Ultimat e Tensile stress	Elastic Modul us					Process/ Material: FDM/Propylene
		%	mm	Deg rees			MPa	MPa					Conclusion:
		20	0.1	45			U=19	E=0.9					Printing Orientation : significant on layer adhesion
		60	0.1	0			22	1.01					Layer thickness: little influence on mechanical properties
		100	0.1	90			27	1.1					The Infill percentage has strong effect on mechanical properties
				±45				1.3					The use of reinforcement is also effective
7	Casavola et al. [16]	Orientati on	Air Gap	Lay er Thi cne ss	Bea d Wid th	No of Cont our Lines		Young's Modulus	Ultimate Tensile stree	Ultimate Tensile stree	Ultimate Tensile stree		Process/ Material
		Degrees	mm	mm	mm	No		GPa	MPa	SD			Orthotropic Characteristics
		0	0	0.35	0.2	2		0.18	32.11	0.3			Conclusion: PLA is stronger than ABS
		45						0.58	26.11	2.37			ABS more brittle
		90						0.11	11.97	3.12			
								0.09	6.71	0.36			
8	Jiang et al [17]	Platform velocity	Material extrusion	Fib er	Ele ctro	Acce pting							Process/Mater ial

	(A)	speed (B)	spacing (C)	spinning concentration (D)	distance (E)							FDM/ABS Conclusion: Optimization of Parameters
	mm/s	mm/s	mm	%	mm							A=16mm/s,
	12	10	0.6	8	60							B=16mm/s,
	14	13	0.8	8.2	70							C=1.4mm,
	16	16	1	8.5	80							D=8.7%,
	18	19	1.2	8.7	90							E=100mm,

From the study it is found that process parameters have significant impact on the properties of the products. The researchers have established functional relationship by applying ANOVA and graph-plot techniques and also applied various optimization techniques to determine optimum level of parameters. The optimum values are summarized in the table 1.

Although no any particular method of optimization is favorable with the researchers yet maximum of them have used the graph-plot method to compare the data and to display the effect directly visible in the pectorals form. Few of them applied one-way ANOVA, box-plot method, Signal to noise ratio(SNR), Grey Correlation degree and Classical laminate theory(CLT) to determine the conclusions, i) layer thickness, ii) percentage infill iii) direction of printing iv) bead temperature v) printing environment vi) filament temperature have significant effect on i) tensile strength ii) ,while other parameters have little or no effect. The techniques applied by researchers are plotted in the below graph.

Figure 5 Graph (Techniques applied Vs % Researchers)

Graph method is most favorable among all the researchers.

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